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Tidal Constants Derivation for Imo River

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ABSTRACT

Tides play critical role in coastal processes, marine operations and navigation. Determination of tidal characteristics and prediction of water levels require knowledge of tide harmonic constants (amplitudes and phase lags) of all relevant tidal constituents. 37 days hourly water level observation was taken at established tide gauge station along Imo River and analysis of observed data using harmonic method implemented with T_Tide. 35 tidal constituents were generated and used for water level prediction. Tidal constants of four principal tidal constituents (K1, O1, M2 and S2) were used to compute tidal form factor and water level datum for the river. The analyses revealed that M2 constituent was the most dominant tidal constituent with amplitude of 0.7375. Computed form factor (0.2076) revealed Imo River to have a semidiurnal tidal regime which is the characteristics of Nigerian coastal waters. The river has a tidal range of 2.231m and mean water level of 1.660m. Comparison of predicted and observed tide gave root mean square error of 0.0177 and correlation coefficient of 0.9943. Results obtained from the study indicated that derived tidal constants are reliable for prediction of Imo River water levels and tide.

Keywords: Imo River, Water level, Harmonic analysis, T_tide, Tidal constant

1.0. Introduction

For navigable channels, standard practices necessary for optimum benefits and deployment of marine based vessels include periodic tidal observation, installation of navigational aids and periodic bathymetry mapping. Information on tides play key role in managing navigational challenges, forecasting water levels (Ekpa *et al*., 2016), and in defining reference level to which hydrographic surveying measurements could be referenced (Rahibulsadri *et al*., 2014). Tidal prediction is essential for planning, design and construction of marine based engineering structures and installation of platforms (Okwuashi and Olayinka, 2017).

To obtain information on the times and heights of high and low water, mean sea level and to predict future water levels, it is necessary that tidal constituents for the location of interest be known. Ideally, tidal constants (amplitude and phase) of relevant tidal constituents are useful for prediction, determination of tidal characteristics and in studying related phenomenon. Studies have been undertaken to analyze time series data in response to obtaining tidal constants useful for tidal prediction. Denney (2012) carried out a study within the Great Bay of New Hampshire based on harmonic analysis of data from four tide gauge stations. From the study, tidal harmonics and tidal datum for the Bay was determined. Badejo and Akintoye (2017) used tidal constituents obtained from least squares tidal harmonic analysis to predict water levels and 5 minutes high and low water heights for Lagos harbour. In the same year, Okwuashi and Olayinka (2017) used Kalman Filter to generate tidal constants for the location. The authors used analyzed harmonic constituents (M2, S2, N2, K2, K1, O1 and P1) to derive a tidal form factor (F) of 0.1955 which correctly predicted the semi-diurnal nature of the study location. In 2019, Piccioni *et al*. (2019) released the TICON dataset which contained 40 tidal constituents of 1,145 globally distributed tide gauge stations. The record keeps track of harmonic constants useful for tidal prediction, tide model evaluation and many other applications. In this study, harmonic analysis method based on least squares fitting was used to analyze observed time series data with the aim of deriving tidal constants for the river and making predictions for future water levels. Objectives of the study included tidal observation, analysis,

prediction and computation of water levels. Trend of tidal range and form factor which described the tidal regime of the river were also determined.

1.1. Study area

The study area for this work was Imo River. The river is one of the significant rivers in the Niger Delta region of Nigeria. Imo River flows over a length of 240 kilometres from it source (Udi Hills) and empties into the Atlantic Ocean at the Bight of Bonny. During high tides, water flows into the river from the Atlantic Ocean and recedes during low tides. Imo River lies between latitudes 4° 28'N and 5° 00'N and longitudes 7° 10'E and 7° 40'E (Figure 1).

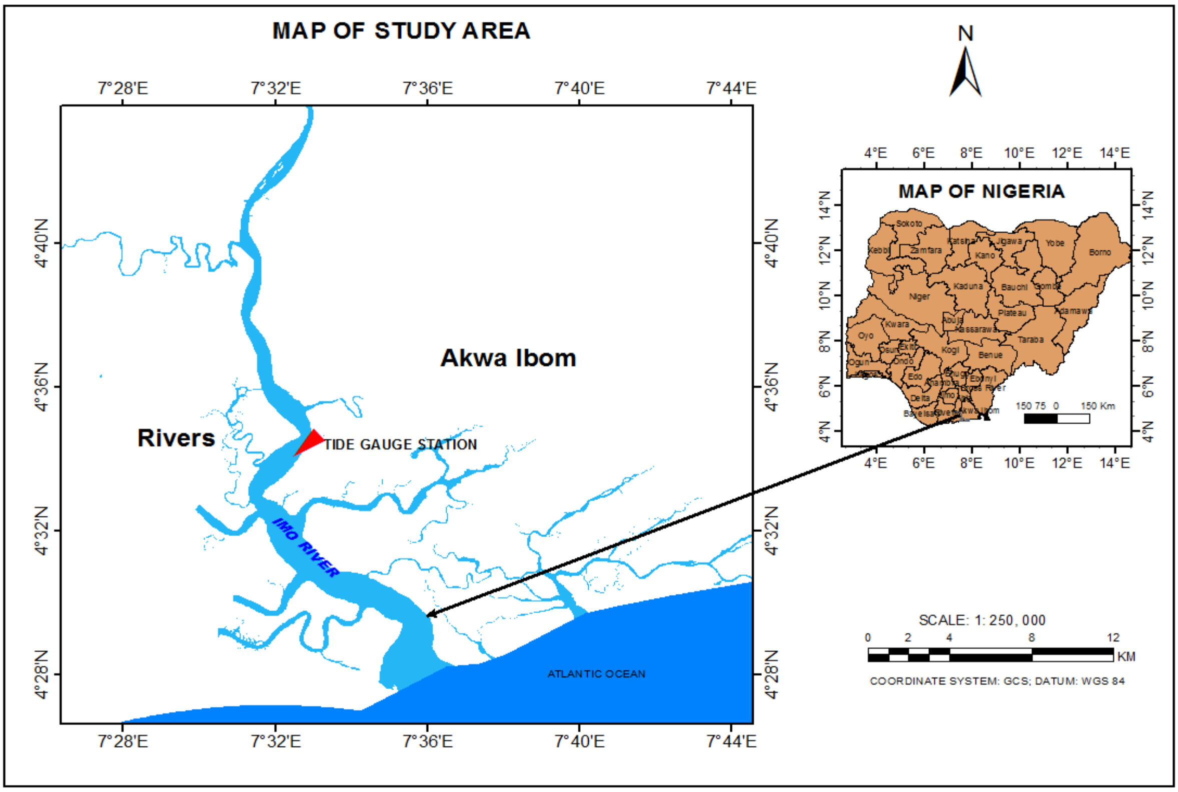


Figure 1: Map showing the study area

The river serves as a natural boundary demarcating four States in Southern (Akwa Ibom and Rivers State) and Eastern (Abia and Imo) Nigeria. Imo River has a vast wetland of 26,000 hectares with estuarine and mangrove ecosystem (Oyo-Ita and Oyo-Ita, 2017). It has a characteristic meandering configuration with many tributaries. The map above (Figure 1) is a map of the river. The location of tide gauge installed during the study is indicated in red.

2.0. Methodology

2.1. Materials

Data used for this study were time series data observed from a manual tide gauge. The tide gauge station was located at latitude 4° 34′ 21.06″ N and longitude 7° 32′ 48.00″E. It was placed strategically close to the ‘Bridge of no Return’ (Figure 2) around the Divisional Marine Police Station Jetty, Ikot Abasi - Akwa Ibom State. The ‘Bridge of no Return’ is a structure of great historical interest and act as a break for the swell incoming Atlantic surge and returning ebb water.

Figure 2: Installed manual tide gauge along Imo River

Figure 2 is a picture of the manual tide gauge installed along the river. Continuous hourly observation of the tide gauge was carried out for 37 days. This was to account for variability effects of phase lag, parallax and declination and also satisfy the Rayleigh criterion (IHO, 2005). Observed time series tidal data covered a period of 865 hours from January 7th 2021 (12:00pm) through February 12th 2021 (12:00pm). The difference between highest and lowest water levels recorded during the period was 2.388m. Tidal curve of observed time series is shown in Figure 3.

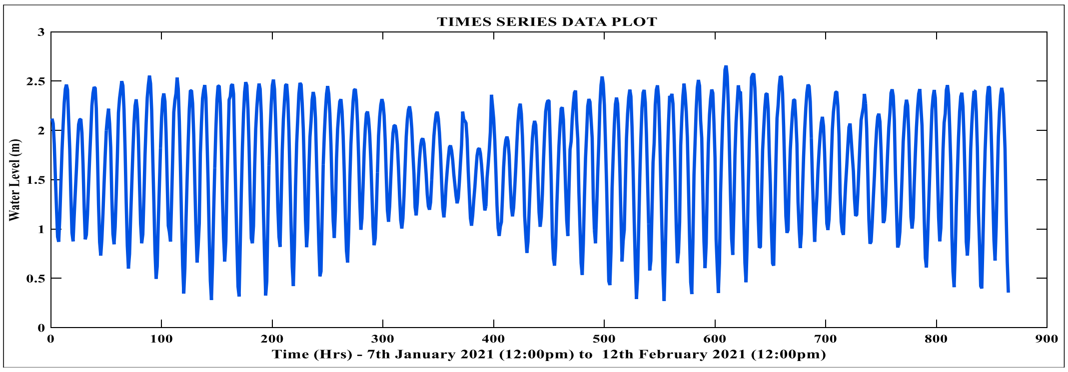


Figure 3: Tidal curve of observed time series data

The tidal curve (Figure 3) is a plot of observed water level data against time. The plot yielded a sinusoidal wave which gave ample information about the observed tide at Imo River. It gave a good assessment of the quality of the observed data.

2.2. Methods

Procedures adopted in the study included acquisition of time series tide data from installed manual tide gauge (Section 2.1), harmonic analysis of tidal constituents, tidal prediction, and analysis of tidal trends. This section discusses tidal analysis and prediction while analyses of tidal trend and characteristics are presented in Section 3.0.

Tidal analysis is the mathematical process by which observed tide at any place is separated into simple harmonic coefficients. It involves the breaking down of tidal signal into component constituents or sinusoids of fixed frequencies (Canadian Coast Guard, 2021). In tidal analysis, derivation of tidal constituents and associated tidal constants [amplitude (H) and phase (α)] which uniquely defines the tide for a given location is based on length of observation (Parker, 2007; Geyman

and Maloof, 2020). Short period observation between seven and fifteen days can only generate four principal tidal constituents (M2, S2, K1 and O1) and nominal mean sea level value. Data observed between one month and one-year usually generate 29 to 70 or more tidal constituents (Morakinyo and Ojinnaka, 2008; Ojinnaka, 2020). Longer time series data help to analyze both harmonic and non-linear hydrodynamic constituents of tide-generating forces (Velikova, 2018). Long observation period also allow more tidal constituents to be included in analysis and for accurate tidal prediction (Parker, 2007; Richter *et al*., 2011). However, the International Hydrographic Organization Standards for Hydrographic Surveys (IHO S-44, 2020) stipulates observation period of not less than 30 days to ensure accurate analysis and prediction. In this study, tidal observation was carried out for 37 days to meet the IHO criteria and also satisfy Rayleigh criterion. Observed time series data was analyzed using the harmonic analysis method. Harmonic analysis method has the advantage of simultaneously solving for all tidal constituents deliverable from a set of time series data at a single processing time (Li *et al*., 2019). It also 'distinguishes frequencies within tidal bands without losing resolution in the time domain or data series' (Matte *et al*., 2013).

Harmonic analysis method uses a priori knowledge of tidal frequencies to break down observed tidal signal into a number of constituent tides of simple harmonic sinusoids (Canadian Coast Guard, 2021). A least square fitting is used to detect tidal frequencies based on the energy exerted by explicit tidal forcing. From priori frequencies, amplitudes and phase lags of each constituent are determined (Matte *et al*., 2013; Abubakar *et al*., 2019). Generally, tide is a superposition of sinusoidal function of three parameters namely frequency, amplitude and phase (Cai *et al.*, 2018). Within an observation period say $t_1 - t_2$, observed tidal signal g(t) can be approximated by the function h(t) such that:

$$h(t) \quad = \quad S_0 + \sum_{t=1}^{n} (H_i cos[\omega_i \, t + \alpha_i]) \tag{1}$$

Where,
h(t) is the water level at time t,
S_o is the height of mean sea level above the datum used,
n is the number of harmonic constituents,
H_i is the amplitude of tidal constituent i,
ω_i is the angular frequency of tidal constituent i,
t is the time or period of tidal constants, and,
α_i denotes the phase lag of harmonic constituent i on the equilibrium tide at Greenwich.

In reality, the moon's orbit is seldom constant but changes over a period of 18.61 years causing a corresponding change in amplitude (H) and phase lag (α) of each harmonic constituent. To account for the effect of lunar nodal cycle on amplitude and phase of the constituents, the nodal factor, f and astronomical argument ($v+u$) are applied. Nodal factor and astronomical argument relate the phase angle to the equilibrium tide in Greenwich since the length of observation used for analysis is usually less than the moon's node epoch (Roos, 1997; Parker, 2007; Badejo and Akintoye, 2017; Ojinnaka, 2020). Introducing the nodal factor and astronomical argument, Equation (1) becomes:

$$h(t) \quad = \quad S_0 + \sum_{t=1}^{n} (f_i H_i cos[\omega_i \, t + (v_i + u_i - \alpha_i)]) \tag{2}$$

From Equation (2), v is the phase angle at time = zero. v changes uniformly based on the hour angle and longitudes of the astronomic tidal forcing. u is the nodal angle and varies gradually due to lunar node variation.

However, there always exists a disparity between the approximated and measured tidal signal at a location. This often arises due to astronomical forcing effect and the influence of non-linear tidal factors. The error is expressed as:

$$\epsilon(t) = h(t) - g(t) \tag{3}$$

Wherefore;
h(t) is approximated tide
g(t) is the measured tide
∈ (t) is analyzed error.

By least squares principle, the error over time period (t_1 –t_2) must be a minimum (Roos, 1997) such that:

$$\int_{t1}^{t2} \in (t)^2 dt \ = minimum \tag{4}$$

This harmonic least square fitting process (Equation 2) was executed with t_tide subroutine tidal analysis library in MATLAB. As a basic input for time series data processing, t_tide requires the start date/time, observation interval and latitude of observation point (tide gauge). Products from t_tide computation include tidal harmonic constituents, frequencies (cycles per hour), amplitudes (meters), confidence intervals of amplitude (meters), phases (decimal degrees - referenced to Greenwich Mean Time), confidence intervals of phase (decimal degrees) and signal-to-noise ratio for the given time series. t_tide also execute nodal corrections and output mean water level (S_o), statistical variance and covariance (Pawlowicz *et al.*, 2002). The analysis function based on t_tide, expressed in MATLAB language is given as:

[NAME,FREQ,TIDECON,XOUT]=T_TIDE(XIN,INTERVAL,START_TIME,LATITUDE,RAYLEIGH) (5a)

Or

[TIDESTRUC,XOUT]= T_TIDE(XIN,INTERVAL,START_TIME,LATITUDE,RAYLEIGH) (5b)

During processing, observed time series data (X) was loaded in MATLAB. Start date/time of observation in MATLAB ‘datenumb’ format and latitude in decimal degree were also provided. The t_tide analysis code was typed in the command window and executed by pressing ‘Enter key’. For easy understanding and recall, the analysis function used was:

>> [NAME,FREQ,TIDECON,XOUT]=t_tide(X,1,DateNumber,Lat) (5c)

Here,‘NAME’, ‘FREQ’ are the names and frequencies of tidal constituents, while ‘TIDECON’ and ‘XOUT’ were derived tidal constituents and mean water (sea) level from the analysis. ‘X’ denote the observed (raw) tide data; ‘1’ was the sample (*i.e.* observation) interval (1hour); ‘DateNumber’ was the start date/ time of tide observation while ‘Lat’ was the latitude of tide gauge in decimal degree. Tidal curve of analyzed data and derived tidal constituents of Imo River are presented in Figure 4 and Table 1 respectively.

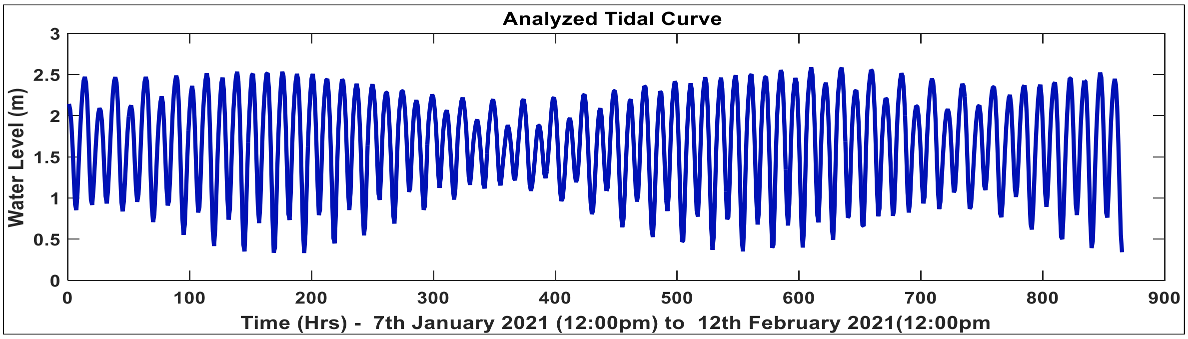


Figure 4: Analyzed tidal curve

Figure 4 is the graph of water levels from analyzed tidal data plotted against time. The graph portrays a smooth sinusoidal signal corresponding to the observed tidal curve (Figure 3). It shows the precision of the analysis result and the fact that tidal constituents so derived were correct representation of the tide generating forces exerted on the river.

With analysis results, prediction of tidal height based on derived and defined tidal constants were carried out using t_tide prediction (t_predic) function. The harmonic Equation (1) was adopted to predict hourly tidal data for one year period covering 01-Jan-2021 01:00:00 to 31-Dec-2021 23:00:00.

3.0. Results and Discussion

From the time series analysis, 35 tidal constituents were extracted which included main tidal constituents and shallow water residual components (Table 1). Extract (Table 2) of the main tidal constituents; O1, K1 M2 and S2 indicated that the amplitude of M2 and S2 which are the semidiurnal constituents were larger and their frequencies double that of K1 and O1 (diurnal constituents). This revealed the semidiurnal tidal characteristics of the river (Ekpa *et al.*, 2016), meaning that two high and two low waters usually occur per day. From Table 2, M2 had the dominant tidal influence with amplitude of 0.7375 m which is far greater than the amplitude of other major constituents (0.4147 m) put together. Total propagated amplitude error for the four main tidal constituents was 0.044 m.

Table 1: Derived tidal constituents of Imo River

Constituents	Frequency	Amplitude, H (m)	Amplitude Error	Phase Lag (°)	Phase Error	Signal-noise-ratio
MM	0.001512	0.0276	0.02	46.23	42.13	1.9
*MSF	0.002822	0.0415	0.019	141.05	27.02	4.8
ALP1	0.034397	0.0065	0.007	131.07	62.77	0.83
2Q1	0.035706	0.0079	0.006	268.93	51.12	1.6
*Q1	0.037219	0.0126	0.008	154.16	38.25	2.3
*O1	0.038731	0.0234	0.008	11.76	23.85	9.5
NO1	0.040269	0.0028	0.006	86.48	130.67	0.25
*K1	0.041781	0.1746	0.01	29.23	2.55	3.30E+02
J1	0.043293	0.0076	0.006	98.72	48.96	1.5
*OO1	0.044831	0.0115	0.007	71.86	37.86	2.9
UPS1	0.046343	0.0051	0.006	105.32	70.64	0.73
*EPS2	0.076177	0.0174	0.011	230.94	42.05	2.3
*MU2	0.07769	0.0391	0.014	222.5	19.8	7.4
*N2	0.078999	0.1228	0.012	151.29	4.92	99
*M2	0.080511	0.7375	0.012	152.32	1.14	3.90E+03
L2	0.082024	0.0171	0.016	133.42	51.6	1.2
*S2	0.083333	0.2167	0.014	206.8	3.44	2.60E+02
*ETA2	0.085074	0.0203	0.012	182.03	31.84	2.8
*MO3	0.119242	0.0139	0.009	73.61	39.34	2.5
M3	0.120767	0.0105	0.009	249.37	50.17	1.4
*MK3	0.122292	0.015	0.01	320.68	33.49	2.2
*SK3	0.125114	0.0146	0.008	72.96	32.19	3.5
*MN4	0.159511	0.0338	0.016	87.85	26.19	4.7
*M4	0.161023	0.1079	0.016	105.77	8.99	48
SN4	0.162333	0.0104	0.011	155.9	81.92	0.88
*MS4	0.163845	0.0545	0.016	187.22	14.53	12
S4	0.166667	0.0121	0.015	301.14	80.39	0.7
2MK5	0.202804	0.0039	0.009	153.07	132.96	0.21
2SK5	0.208447	0.0007	0.006	142.04	249.73	0.014
2MN6	0.240022	0.0098	0.009	117.2	47.25	1.2
*M6	0.241534	0.0176	0.008	99.44	24.93	4.5
*2MS6	0.244356	0.0218	0.008	204.96	21.57	7.4
2SM6	0.247178	0.006	0.007	279.2	77.71	0.75
3MK7	0.283315	0.0065	0.007	349.11	54.92	0.95
M8	0.322046	0.0058	0.005	112.91	50.03	1.2

Table 2: Derived harmonic constants of main tidal constituents

Tidal Constituent	Amplitude (m)	Phase (°)	Description
O1	0.0234	11.76	Lunar declinational diurnal constituent
K1	0.1746	29.23	Luni-solar declinational diurnal constituent
M2	0.7375	152.32	Principal lunar semidiurnal constituent
S2	0.2167	206.8	Principal solar semidiurnal constituent

Figure 5 reveals the magnitude of generated tidal constituents as an indication of their relative contribution to the type of tide experienced within the study area while Figure 6 shows the magnitude of amplitudes and phases of the four principal tidal constituents. Among the significant dominant tidal

constituents, M2 had about 64 % contribution to the local tide while S2 lead with the largest phase lag. The semi-diurnal species (EPS2, MU2, N2, M2, L2, S2 and ETA2) contributed significantly with amplitudes ranging between 1.71cm and 73.75cm. Amplitudes of compound and overtides (MO3, M3, MK3, SK3, MN4, M4, SN4, MS4, S4, 2MK5, 2SK5, 2MN6, M6, 2MS6, 2SM6, 3MK7, M8), the shallow-water constituents were between 0.07cm and 10.79cm. The compound and overtides revealed components part of the tide caused by shallow water nonlinear hydrodynamic effects taking place within the river. The first overtide of M_2 constituent, M_4, had the largest amplitude of 10.79cm (Figure 5) followed with MS4, the compound tide of M_2 and S_2 with amplitudes of 5.45m indicating that the river morphology and bathymetry contributed to the local tide. The analysis result revealed the need to observe tide for long period of time to properly analyze the various factors that contributes to tide at the location. The result also proved the research reports (Parker, 2007; Richter *et al*., 2011) that the number and type of tidal constituents deliverable from harmonic analysis is a function of the length of tide data used. This also supported the fact that accurate prediction requires longer time series data and use of many tidal constituents in the prediction (Parker, 2007).

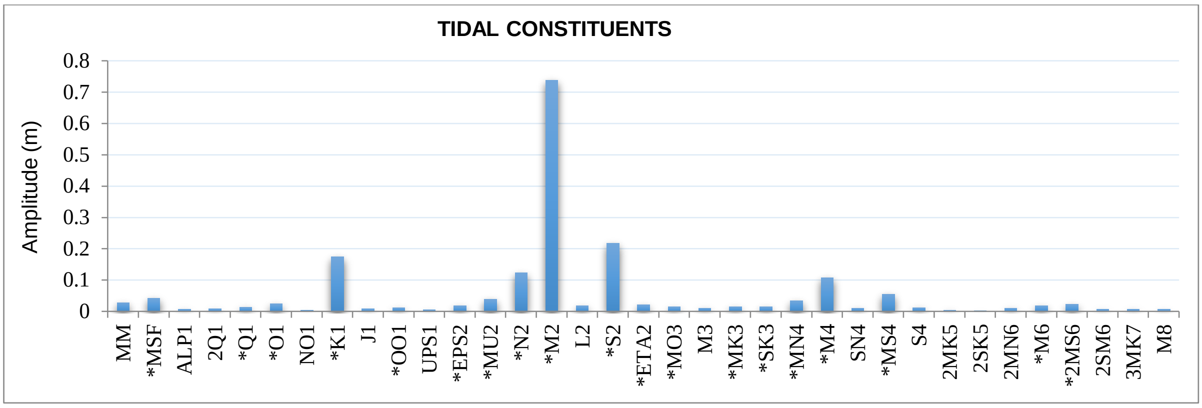
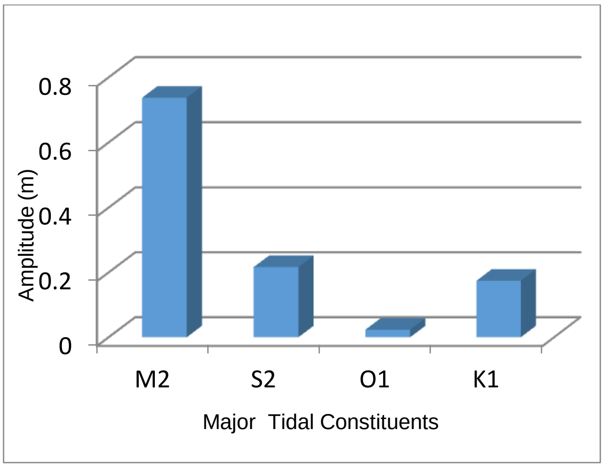
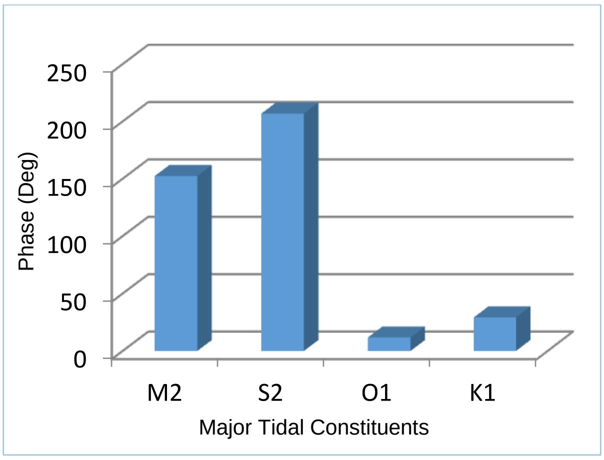


Figure 5: Amplitude of tidal constituents for the study site



(a)



(b)

Figure 6: Amplitude (a) and phase (a) of major tidal constituents

To determine the tidal regime of the river, the tidal form factor was computed. Form factor (F) is a ratio of the sum of amplitudes of diurnal and semidiurnal tidal components (Ojinnaka, 2020). The form factor is given by:

$$F = \frac{K_1 + O_1}{M_2 + S_2} \tag{6}$$

Based on the form factor, tides are characterized as:

F < 0.25 - semi-diurnal
0.25 < F < 1.50 - mixed, mainly semi-diurnal
1.50 < F < 3.00 - mixed, mainly diurnal
F > 3.00 - diurnal

Amplitude values of K_1, O_1, M_2 and S_2 from table 2 were substituted in equation (6) and the form factor computed as:

$$F = \frac{0.1747 + 0.0234}{0.7375 + 0.2167} = \frac{0.1981}{0.9542} = 0.2076$$

The result (0.2076) indicated semidiurnal tidal nature of the river as reported by Ekpa *et al*. (2016) and corroborates Dike and Agunwamba (2012) assertion that tides in Niger Delta region were mostly semidiurnal. This also confirmed other research findings (Ojinnaka, 2013; Okwuashi and Olayinka, 2017) that Nigerian and West African coastal waters have semidiurnal tidal regime.

Investigation of water level trend of the river included determination of range, mean spring and mean neap range, mean tidal range, mean water and mean tidal level. Predicted tidal data covering the period of observation were extracted and used for the analysis. The range of predicted tide given by highest water level (HWL) less the lowest water level (LWL) for the period of observation was 2.231m. Trend of tidal range for the river based on mean range of tide (1.758m) showed that the river was a meso tidal river. Mean tidal level (1.534 m) differed from average water level (1.660m) above chart datum by -0.13cm. Mean spring range and mean neap ranges obtained were 1.9084m and 1.0416m respectively.

Accuracy of prediction results were evaluated by analyzing the residuals between observed time series and predicted tide. Predicted tide values covering the period of observation (January 7th 2021 - February 12th 2021) were used for the analysis. The two statistical tools used for the test were root mean square error (RMSE) and coefficient of correlation (r). Root mean square error (RMSE) was computed using Equation (7) while coefficient of correlation (r) was determined based on Equation (8).

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(P_i - O_i)^2}{n}} \tag{7}$$

$$r = \frac{\sum_{i=1}^{N}(x - x)(y - y)}{\sqrt{\sum_{i=1}^{N}(x - \ddot{x})^2 \; \sum_{i=1}^{N}(y - \ddot{y})^2}} \tag{8}$$

Where *p* is the predicted tidal value for the observations, *o*, observed time series data and n is the number of observations. x and y were observed and predicted tide values while ẍ and ÿ were the mean of observed time series data and predicted tide values respectively. The computed RMSE was 0.0177 while computed r was 0.9943.

Figure 7 depicts the tidal curve of computed residuals. From the curve, the residuals lie between ±0.4m. The least residual was -0.3963 m while largest residual was 0.2803m. The average residual value was -0.0012m

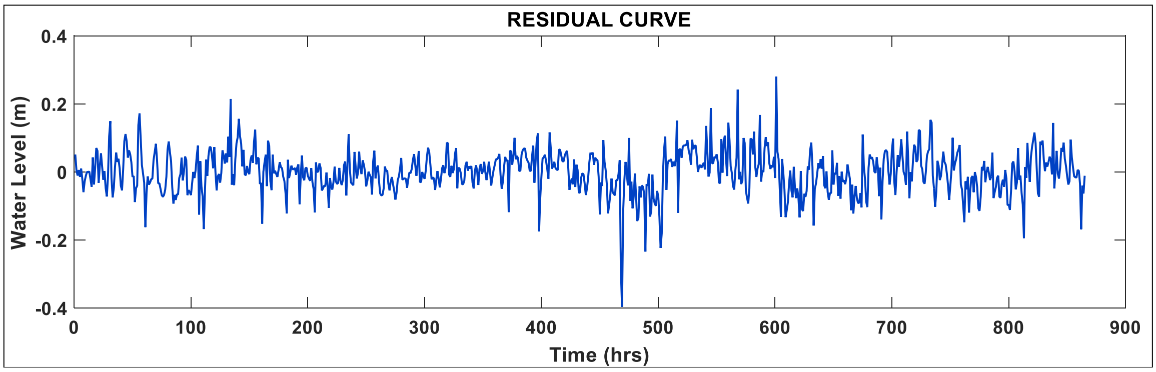


Figure 7: Plot of residuals between observed time series and predicted tide

4.0. Conclusions

Analysis of time series tide data was carried out by least squares harmonic method to derive tidal constants for Imo River. Tidal constants (amplitude and phase) for 35 tidal constituents and mean water level of 1.660m were obtained. One-year tidal prediction was carried out based on derived constants. Investigation on the tidal characteristics of the river showed that Imo River has mean spring and mean neap ranges of 1.9084m and 1.0416m respectively. A form factor of 0.2076 obtained indicated a semidiurnal tidal regime which is the characteristics of Nigerian and West African coastal waters. Computed RMSE of 0.0177 was closed to 0 while result of r (0.9943) revealed a very strong correlation of predicted values to the observed time series. These results indicated a good fit between predicted and observed tide. To enhance long period observation and investigation on the stability of obtained tidal constants, establishment of automatic tide gauge along the river is recommended.

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